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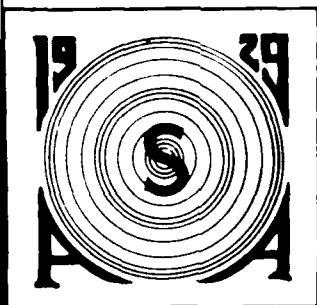
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High-frequency bistatic reverberation was measured from a smooth, sandy, featureless bottom located 19 miles south of Panama City, FL. Bistatic scattering variability is presented as a function of frequency (20–180 kHz), grazing angles (9.5° – 30°), and small horizontal and vertical bistatic scattering angles. Results show that bistatic variabilities tend to decrease with decreasing grazing angles and decreasing source beamwidths. Possible explanations for these decreasing variations are also presented.

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INTRODUCTION

Active high-frequency shallow-water sonar applications require high-resolution characterizations of ocean bottom reverberation, including estimates of both monostatic and bistatic scattering strengths. Bistatic scattering may be the dominant mechanism that degrades interelement and interbeam receiver coherence that sets limits on array processing gain.

High-frequency bottom scattering as a function of frequency, grazing angle, pulse length, and environmental conditions have been reported by numerous authors.^{1–6} However, these authors have not reported any bistatic results. Nolle *et al.*⁷ made a series of scattering measurements in a sand-filled tank using separate transmitting and receiving systems but reported only monostatic results. Urlick^{8,9} conducted a series of bistatic measurements in two areas off the coast of Florida. In both areas, Urlick found that bistatic scattering showed little dependence on bistatic angles. A series of small angle bistatic measurements taken east of Jacksonville, FL, was reported by Stanic *et al.*¹⁰ These results also showed little dependence of bistatic scattering on bistatic angles. However, variations in bistatic scattering strength decreased with decreasing grazing angles. A weak bistatic scattering frequency dependence was also reported.

Zabul *et al.*¹¹ and Martin¹² conducted a series of theoretical investigations into the angular and frequency spreading of an acoustic field scattered from a rough surface. Neither Zabul nor Martin compared their results to experimental data. Recently, Restrepo and McDaniel¹³ developed two spatial covariance models and compared their out-of-plane scattering results using flat surfaces and rough surfaces with Gaussian roughness spectra. Comparison of intensity was good only if the surface was very rough, or the direction specular. The results were presented for large bistatic angles and made no data comparisons. Ellis and Crowe¹⁴ calculated bistatic reverberation using a three-dimensional scattering function but made comparisons only to measured low-frequency, deep-water reverberation.

This paper presents high-frequency small angle bistatic scattering results from an experiment conducted in a flat sandy area 19 miles south of Panama City, FL. These mea-

surements were made as a function of frequency (20–180 kHz), grazing angle (9.5° – 30°), and small horizontal and vertical bistatic scattering angles. Levels at each hydrophone were compared to levels at a reference hydrophone and the difference presented as horizontal and vertical scattering strength variations. Monostatic scattering strength results are given in Ref. 15. These bistatic results are compared to similar bistatic results reported by Stanic *et al.*¹⁰ Possible explanations for the observed results are also presented.

I. EXPERIMENTAL MEASUREMENTS

The experimental area was located using side scan sonar surveys and underwater television scans. Small-scale features of the experimental site were characterized using data provided by stereophotography and sediment core analysis. These techniques are outlined in Ref. 16. Bistatic scattering measurements were made using a 12 hydrophone two-dimensional spatial receiving array and a pair of nonlinear parametric sources. The orientation of the receiving array and sources were controlled by a three-axis positioning system. The positioning system was mounted on top of a 7.6-m-high undersea tower. Figure 1 shows the configuration of the transmitting and receiving arrays. The 450-kHz source transmitted difference frequencies between 180 and 90 kHz/WB (widebeam). The 250-kHz source transmitted difference frequencies between 90 kHz/NB (narrow beam) and 20 kHz. Beamwidths for both sources are given on Table I. Source levels ranged from 180 dB r_0 1 μ PA at 20 kHz to 214 dB r_0 1 μ PA at 180 kHz. The measurements were made using 5-ms-long cw pulses. The receiving hydrophones were EDO model 6660 omnidirectional units with integrated filters and preamplifiers. Data from each of the 12 hydrophones were base banded to 5 kHz and simultaneously digitized at 20 kHz. For each hydrophone channel and experimental configuration, 50 scattered signal envelopes were averaged, a mean envelope level was estimated and the standard deviation calculated.

Figure 2 is a schematic of the horizontal and vertical scattering geometry. The range along the maximum response axis (MRA) of the sources is given by R . Here, R and R_{\perp} are the ranges between the hydrophones and the

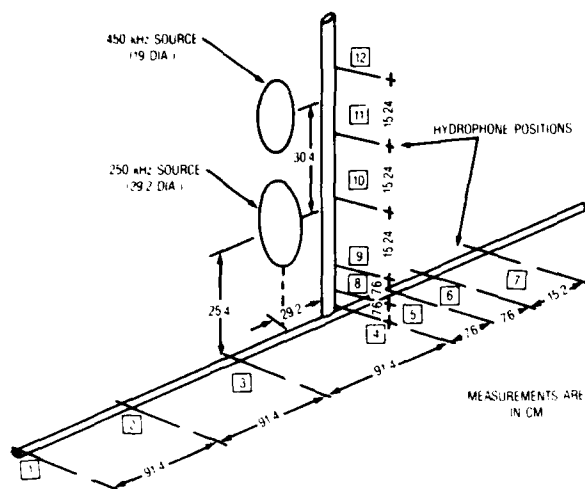


FIG. 1. Source and receiver array configurations.

estimated center of the insonified area (A). The horizontal and vertical bistatic scattering angles are given by $\theta \pm_h$ and $\theta \pm_v$. The sign designates which side of the source MRA a hydrophone is located. The grazing angle is given by θ_g . The average bistatic scattering strength is given by

$$BS = RL - SL - TL_1 - TL_2 - 10 \log A,$$

where RL is the average received level, SL is the source level at 1 m along the MRA, TL_1 is the transmission loss along R , TL_2 the transmission loss along R_h or R_v , and A is the insonified area.

For data taken in the horizontal plane, the level at hydrophone 4 was used as the reference level. This hydrophone was located closest to the vertical axis of both sources. For data taken in the vertical plane at frequencies between 180 kHz and 90 kHz/WB (450-kHz source) and at a grazing angle of 30° , the reference hydrophone was number 11. For all other vertical measurements, the reference hydrophone was number 10.

II. EXPERIMENTAL RESULTS

The experimental area was a large homogeneous, featureless, hard-packed sandy bottom. Figure 3 is a photograph of the experimental area. The average sediment properties are given in Table II. Figure 4 shows two results

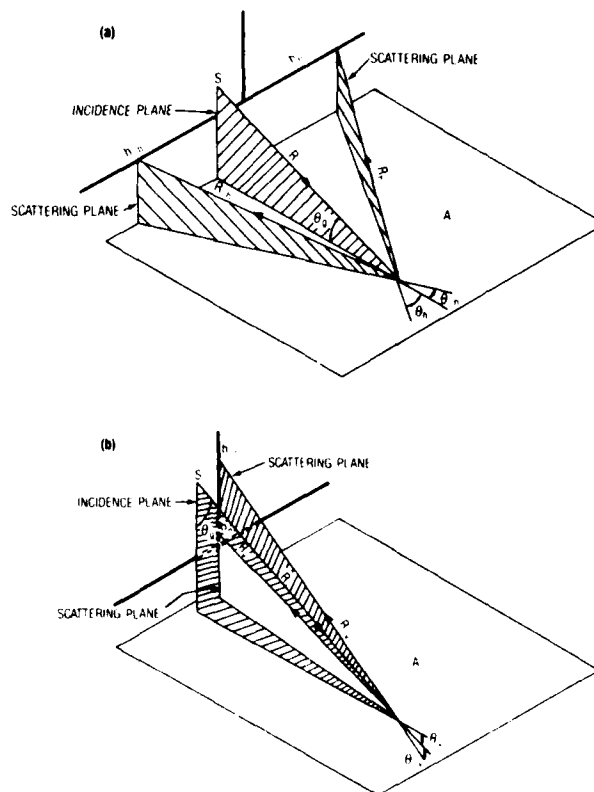


FIG. 2. Horizontal and vertical bistatic scattering geometry.

of bottom roughness spectra (S) from the analysis of the stereophotographs. These spectra represent the extremes in bottom roughness that were present in the experiment area. These spectra have $f^{(-2.2)}$ and $f^{(-1.8)}$ frequency dependencies. This 0.42 range of dependencies is about half the range measured during the Jacksonville experiments.

TABLE I. Source beamwidths as a function of frequency

	Frequency (kHz)	Beamwidth (-3 dB)
250-kHz source	20	2.5
	40	2.0
	60	1.5
	90 WB	1.2
450-kHz source	90 WB	2.75
	10	2.2
	150	2.0
	180	2.0



FIG. 3. Typical photograph showing the smooth bottom at the experimental site (58×27 cm).

TABLE II. Average values of sediment parameters in the upper 20 cm.

Velocity ratio	1.133
Porosity	39.0%
Mean grain size (mm)	0.166
Compressional wave attenuation at 400 kHz	234.0 dB/m

A. Horizontal bistatic scattering

Figure 5 shows the measured high-frequency horizontal bistatic scattering variations as a function of frequency (180, 150, 110, and 90 kHz/WB), grazing angle (30°, 20°, and 9.5°), and small horizontal bistatic scattering angles (−10.2° to 1.14°). These measurements were made using the 450-kHz source. The data points are at the positions of the receiving hydrophones measured as a function of bistatic angles. The data at each bistatic angle are the differences between the average level at that hydrophone and the average level at the reference hydrophone located closest to the maximum response axis of the source. This reference hydrophone was labeled as 0°. For clarity, the horizontal scale for positive bistatic angles has been expanded. At a grazing angle of 30° the bistatic variations are between 8.2 and −12.5 dB. The variations are between 3.5 and −13.3 dB at a grazing angle of 20° and between 8.8 and −8.8 dB at a grazing angle of 9.5°.

Figure 6 shows the low-frequency (90 kHz/NB, 60, 40, and 20 kHz) horizontal bistatic scattering variations as a function of grazing angles (30°, 20°, and 9.5°) and bistatic

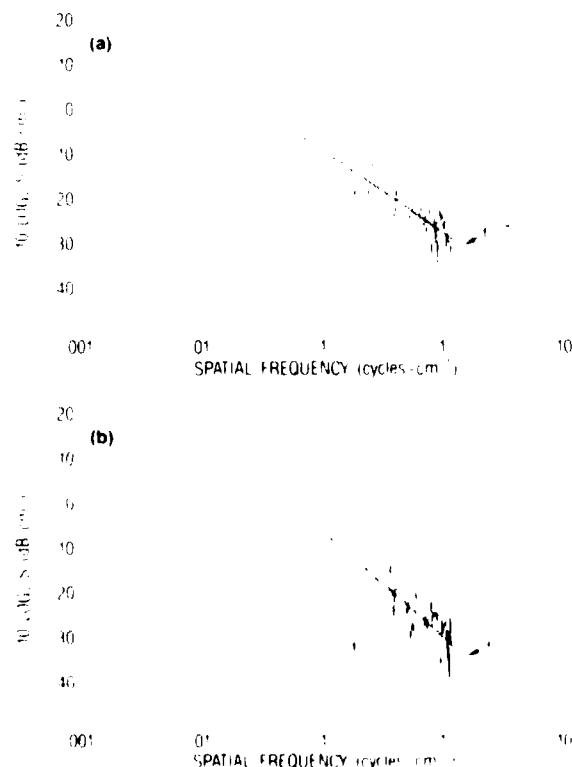


FIG. 4. Surface roughness spectra for two different areas.

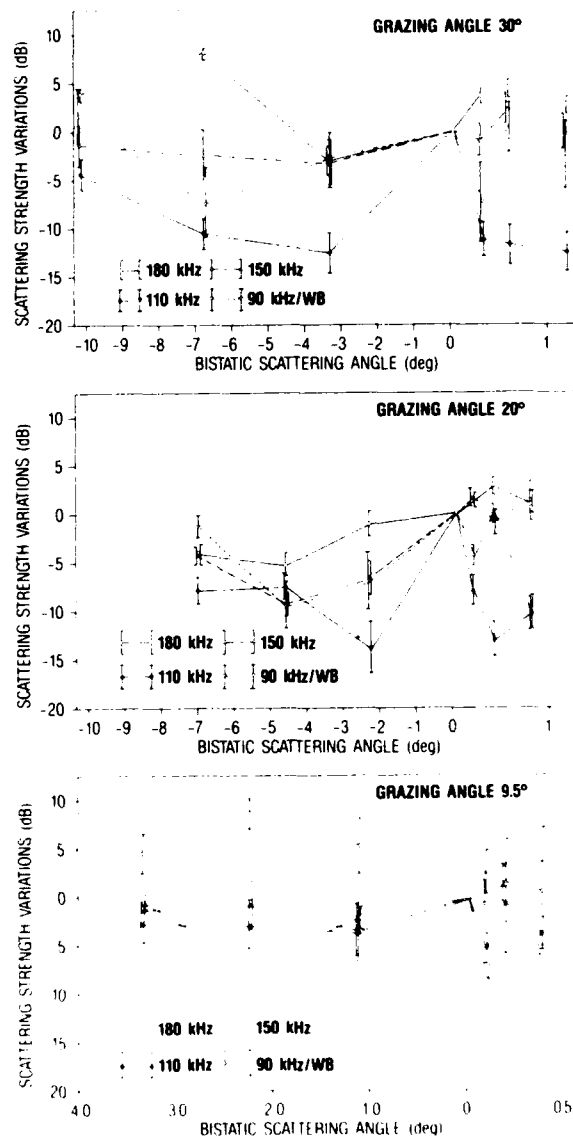


FIG. 5. High-frequency horizontal bistatic scattering variations.

scattering angles (−10.2° to 1.14°). These measurements were taken using the 250-kHz source. The horizontal scale has again been expanded for positive bistatic angles. At 30°, the bistatic variations were between 8.4 and −14.0 dB. At grazing angles of 20° and 9.5° the bistatic variations were between 7.1 and −9.9 dB and between 3.6 and −6.7 dB, respectively. Low source levels at 20 kHz did not allow for consistent bistatic measurements at a grazing angle of 9.5°.

Figure 7 shows the range of horizontal bistatic scattering variations as a function of frequency and grazing angle (the 90-kHz/WB data was used). The frequency dependence of these variations is 0.03, 0.04, and 0.01 dB/kHz for grazing angles of 30°, 20°, and 9.5°, respectively.

The error bars shown in Figs. 5, 6, and all others are the standard deviations of the measured data. Since a stable platform was used, the ping-to-ping fluctuations in the

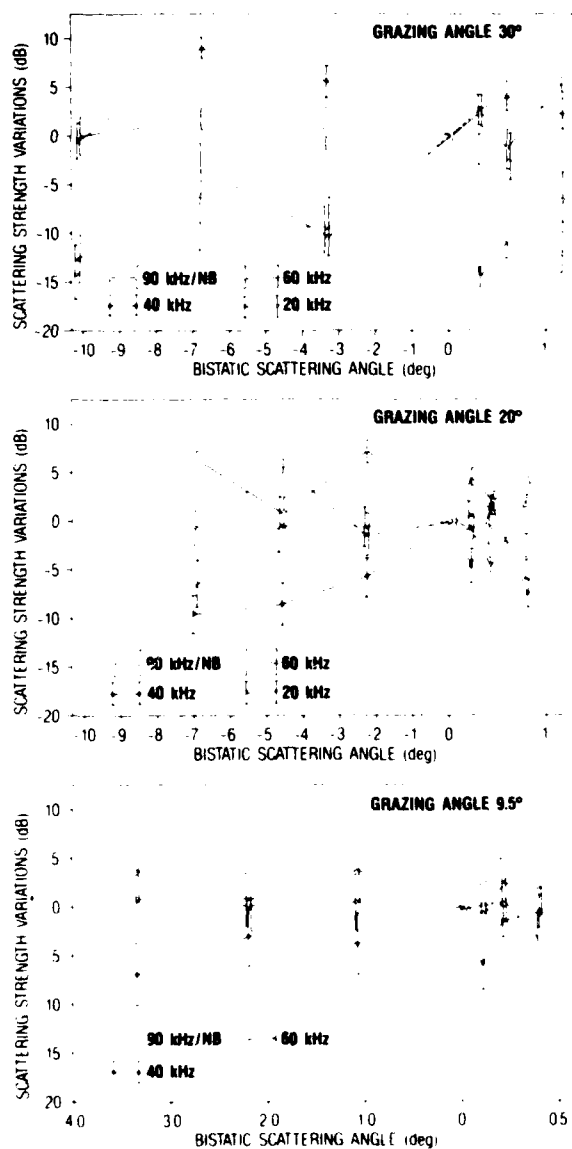


FIG. 6 Low-frequency horizontal bistatic scattering variations

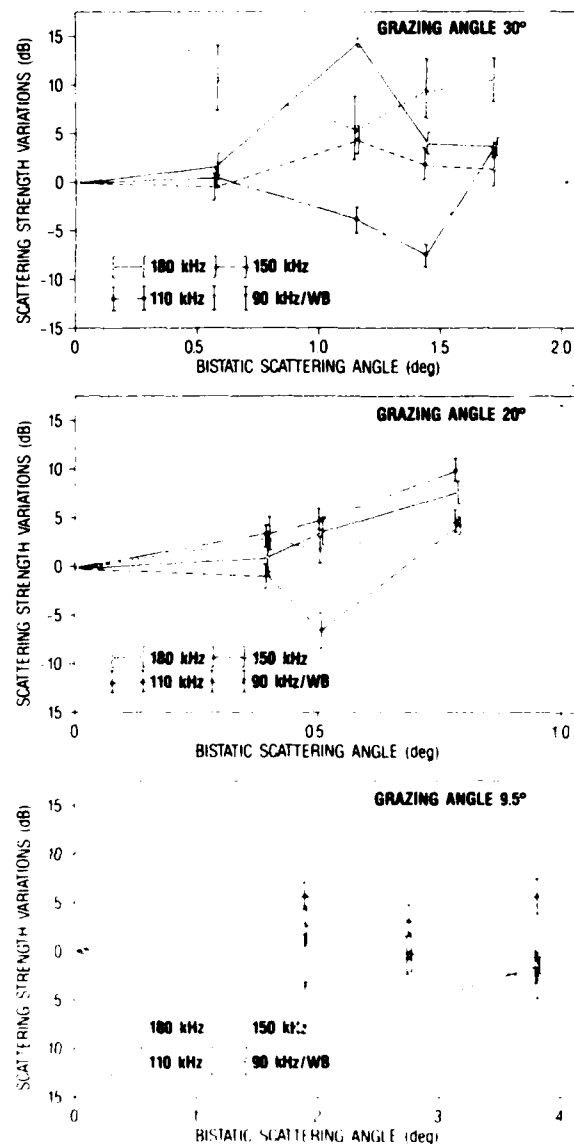


FIG. 8 High-frequency vertical bistatic scattering variations

measured data were due to small fluctuations in the index of refraction of the water column. These fluctuations cause small displacements in the position of theinsonified areas resulting in ping-to-ping envelope level variations. No standard deviations are shown for the reference hydrophones.

B. Vertical bistatic scattering

Figure 8 shows the high-frequency vertical bistatic scattering variations as a function of frequency (180, 150, 110, and 90 kHz/WB), grazing angles, (30°, 20°, 9.5°), and small vertical bistatic angles (0.57° to 1.71°). At a grazing angle of 30° the vertical bistatic scattering variations are between 14.5 and -7.1 dB. This range is 0.9 dB greater than the horizontal variations at 30°. At the 20° grazing angle, the vertical variations are between 10.6 and -6.3 dB. This range is 0.1 dB larger than the corresponding

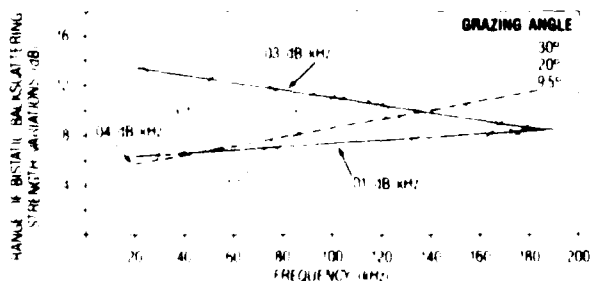


FIG. 7 Range of horizontal bistatic scattering variations

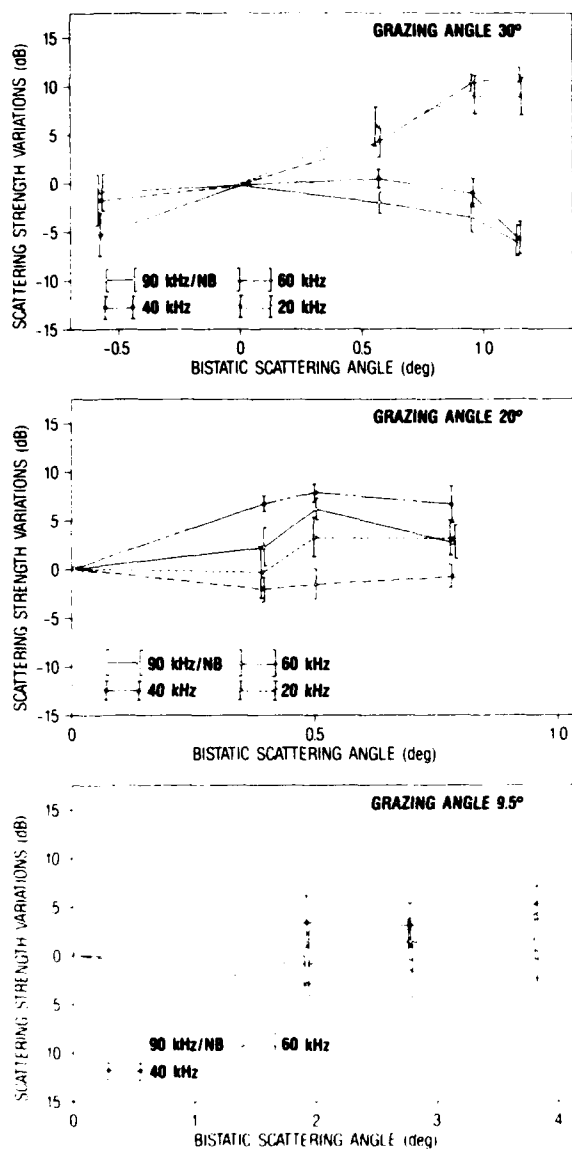


FIG. 9. Low-frequency vertical bistatic scattering variations

horizontal variations. The vertical variations at a grazing angle of 9.5° are between 5.9 and -5.2 dB. This range is 6.5 dB smaller than the horizontal variation at 9.5°.

The low-frequency (90 kHz/NB, 60, 40, and 20 kHz) vertical bistatic variations as a function of grazing angles (30°, 20°, 9.5°), and bistatic angles are shown in Fig. 9. At a grazing angle of 30°, the vertical variations are between 10.6 and -5.7 dB. This is 1.8 dB less than the corresponding low-frequency horizontal variations. The variations at grazing angles of 20° and 9.5° are between 7.7 and -2.1 dB and 5.4 and -2.8 dB, respectively. These variations are 7.2 and 2.1 dB less than the horizontal variations at 20° and 9.5°.

The range of vertical bistatic variations as a function of frequency and grazing angle is shown in Fig. 10 (the 90-kHz/WB data were used). The frequency dependence at

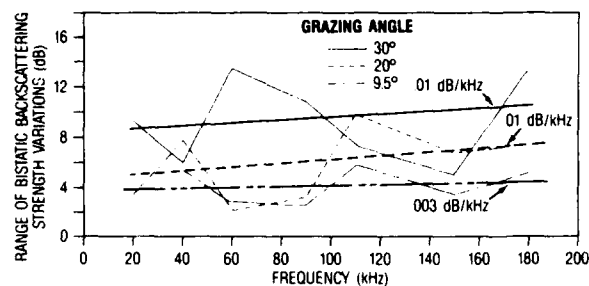


FIG. 10. Range of vertical bistatic scattering variations.

grazing angles of 30°, 20°, and 9.5° are 0.01, 0.01, and 0.003 dB/kHz, respectively.

C. Beamwidth dependence

Figure 11 shows the beamwidth dependence of the horizontal bistatic scattering variations for a source frequency of 90 kHz. At 90 kHz/NB, the 250-kHz source had a beamwidth of 1.2° and at 90 kHz/WB the 450-kHz source had a beamwidth of 2.75°. The horizontal scale was again expanded for positive bistatic angles. In general, the bistatic scattering variations measured using the narrow-beam source were less than those measured using the widebeam source.

The vertical bistatic variations at 90 kHz as a function of beamwidth and grazing angle are shown in Fig. 12. At a grazing angle of 30°, the variations using the narrow-beam source were significantly less than those measured using the widebeam source. At grazing angles of 20° and 9.5°, the differences were very small.

III. DISCUSSION

In this paper, we have addressed small-angle, high-frequency, bistatic bottom scattering. Our results have shown that unlike the horizontal results measured at Jacksonville,¹⁰ the range of horizontal bistatic scattering varia-

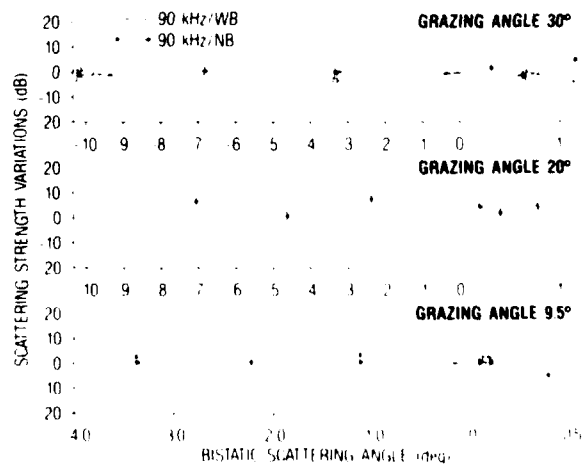


FIG. 11. Beamwidth dependence of horizontal bistatic scattering variations at 90 kHz

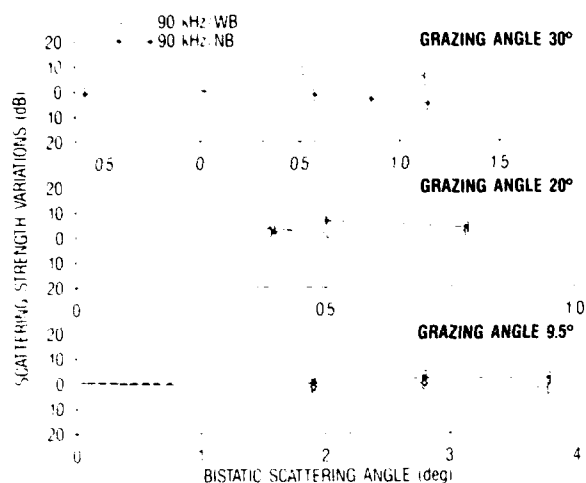


FIG. 12 Beamwidth dependence of vertical bistatic scattering variations at 90 kHz

tions measured at Panama City did not always decrease with decreasing grazing angle. At a grazing angle of 20°, the range of variations was larger than the bistatic variations at grazing angles of 30° and 9.5°. The frequency dependence of the Panama City bistatic data at a grazing angle of 30° had a negative frequency dependence. At this time, the reasons for this negative frequency dependence and for the large bistatic variations at 20° are not clear. Generally, the bistatic results measured at Panama City were 1 to 5 dB higher than the Jacksonville results.

The difference in bistatic scattering variations measured using the 90-kHz/NB and 90-kHz/WB sources can be attributed to the difference in the size of the insonified area and the difference in the number of the individual scatterers in each area. At each grazing angle, the small areas insonified by the 90-kHz/NB source had few individual scatterers that would tend to cause significant bistatic scattering effects. As suggested by Stanic *et al.*,¹⁰ the decrease in bistatic scattering strength variations as a function of range (except the horizontal results at 20°) may also be linked to the small sizes of the individual scatterers. As the acoustic wavelengths became larger and the grazing angles decreased, the seafloor began to appear smooth and thus may have had less effect on the angular scattering of the acoustic energy.

Urlick⁷ found that for another sandy area off Panama City, FL, there was a maximum of 10-dB variation in the bistatic scattering levels as a function of bistatic angle at 22 kHz. The variations at our Panama City site were significantly larger than 10 dB. Only at frequencies below 90 kHz

and at grazing angles less than 20° were the variations 10 dB or less. The results presented in this paper, and in Ref. 10, clearly demonstrated that the bistatic mechanisms are complex and have not been clearly identified.

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